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PSS Sustainability Assessment and Monitoring framework (PSS-SAM) – Case study of a multi-module PSS Solution

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Abstract

Business-to-business Product Service System (PSS) solutions are characterized by intensive interaction among PSS providers, suppliers, and customers, as well as an integration of physical and immaterial solution modules. These factors increase the complexity and interdisciplinary of such offerings. Furthermore, the characteristics complicate sustainability assessment and monitoring of PSS, as environmental, social, and economic concerns have to be integrated into a PSS by minimizing negative impacts of the PSS on these three axes throughout the PSS lifecycle. The indicator-based framework „PSS Sustainability Assessment and Monitoring (PSS-SAM)" has been specifically developed to support managers and decision makers in dealing with the complex situation described above. This framework considers the most important sustainability aspects throughout the entire PSS lifecycle and adheres to European standard requirements. The results of a previous work have already confirmed the usability of the framework to assess the sustainability of one PSS module (availability of spindle) within a single PSS lifecycle phase (operating phase). The aim of this paper is to present the improvements of the PSS-SAM framework that facilitate sustainability assessment of PSS solutions with multiple modules throughout their entire lifecycle. The improved framework has been validated by a case study of an industrial micro-production PSS solution including multiple modules (spindle, maintenance, training, etc.). The long-term goal is to develop IT solutions that support the sustainability assessment of PSS.

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Keywords: Product Service System (PSS); sustainability assessment; business-to-business PSS; PSS lifecycle; multi-module PSS solution.

1. Introduction

Business-to-business PSS solutions show characteristics such as interdisciplinary work, participation of PSS providers in customers" ongoing operations, etc. [1].

With regards to sustainability, today there is a strong increase in research to integrate sustainability aspects into industrial activities [1, 2]. For example, the work of Warhurst [3] focuses on the development and use of sustainability performance indicators in mining companies and takes into account the perspectives of internal and external stakeholders. The framework proposed by Epstein and Roy [4] provides an approach to examine the drivers of corporate sustainability, the relations to stakeholder reactions, and long-term financial performance. The method called „balanced scorecard" [5] has been extended to a sustainable balanced scorecard approach by including environmental and social performance indicators and aggregating all indicators into an overall sustainable performance index.

Unfortunately these works are not specific to business-to-business PSS solutions or they only take a broad and abstract perspective. Therefore, aspects relevant to PSS (such as customer-related processes and organization) are usually not considered. In addition, some works only consider part of the requirements for sustainability assessment of these kinds of solutions [1].

Furthermore the integration of sustainability into international standards is nowadays mainly limited to policies and frameworks on a governmental level [6, 7]. First approaches for sustainability management at company level are proposed by VDI [8]. Life Cycle Assessment (LCA) is the most standardized framework dealing with sustainability

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aspects and the most supported by IT solutions. Unfortunately, it is focused on environmental aspects [9]. Even if the solution bundle of goods and services is considered, this framework is not specific to the integrated development of PSS.

In the area of PSS, most existing publications discuss the impact of PSS on sustainability [10, 11], dealing with the question of whether PSS are really sustainable [12], or with the sustainability benefits of PSS [13, 14, 15]. Different strategies of maximizing the social and environmental performance in offering PSS are also described [13]. Although this research takes into account all sustainability dimensions, the question of „how the sustainability of PSS can be measured and controlled“ has not been addressed yet.

In order to support managers and decision makers in sustainability assessment of business-to-business PSS, the framework „PSS Sustainability Assessment and Monitoring (PSS-SAM)“ has been developed. PSS-SAM considers all (i.e. social, economic, and ecological) sustainability dimensions throughout the entire PSS lifecycle in different domains such as mechanic, electronic, and immaterial modules (e.g. services). It takes into account the requirements of EU and German standards (DIN, VDI, etc.) alike.

2. The PSS-SAM framework

2.1. General description

The proposed Sustainability Assessment and Monitoring (SAM) framework is based on a robust control systems approach. The following figure provides an overview of its main stages:

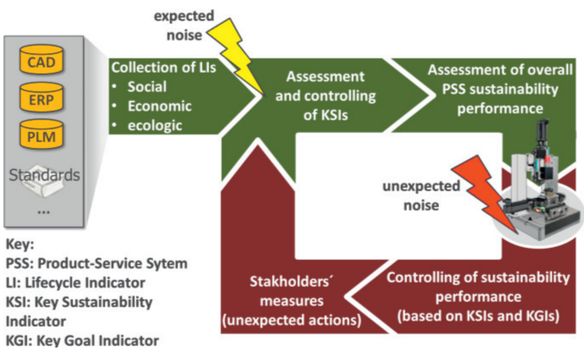

Fig. 1. PSS-SAM main stages.

The structure and indications of the proposed framework have many aspects in common with standardized assessment frameworks such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). However, due to the characteristics of PSS, the framework shows important differences. First, in order to ensure the monitoring of PSS solutions, the framework follows a control loop. Input information is permanently derived from various sources and transformed into PSS Lifecycle Indicators (LI). The goals and scope of the assessment are permanently updated based on the specific choice of LIs. According to company-specific targets, an individual rating is defined for each LI. A suitable combination of LIs and their respective rating define the Key Sustainability Indicators (KSI) [1].

Analogous to the „inventory analysis“ and „impact assessment“ LCA stages, information is analyzed and aggregated in the „sustainability assessment“ stage. First, KSIs are assessed and controlled. The overall sustainability performance of a PSS solution is obtained as output information. This considers the relations and mutual dependencies among different KSIs [1].

Finally, in the last stage of the „controlling“ framework, assessment results are provided to the stakeholders. KSIs are compared to Key Goal Indicators (KGIs) to check whether they are within the acceptable margins. If that is the case, the stakeholder is not expected to take action. In contrast, if PSS sustainability is out of proportion, stakeholders have to take appropriate action. In addition to this, the system can be disturbed by expected or unexpected noises. Unexpected noises are disturbances that have not been taken into account during the development phase of the PSS. Therefore, appropriate action has to be developed during the operating phase. If expected noises (e.g. a power failure) occur, predefined action is taken to resolve the problem. Both expected and unexpected noises affect PSS sustainability [1].

Considering the results of the previous case study (sustainability assessment of single module PSS solutions within a single PSS lifecycle phase [1]), different points of the PSS-SAM framework have been improved. The most important improvements comprise the following three aspects:

Approach for data quality evaluation: Since the quality (more precisely: the reliability) of data defines the reliability of the assessment results, the improved framework proposes solutions for the classification and evaluation of data quality.

Consideration of PSS provider, customer and supplier perspectives: However, PSS providers, customers, and suppliers may be interested in different KSIs. For this reason, the framework has been adapted to consider different perspectives by enabling PSS providers, customers, and suppliers to choose their own KSIs and KGIs. These indicators can also be lifecycle phase specific.

Guidelines for the definition of measures: Regarding measure definition, the improved framework suggests searching for critical points and defining measures in PSS-relevant domains such as manufacturing-related processes, the product development stage, the company-organizational model, etc.

The next chapter outlines the above improvements illustrated by the new case study of a multi-module PSS.

3. Case study of a multi-module PSS solution

3.1. Overview of the PSS solution

For the validation of the improved PSS-SAM framework, a conceptual case study has been carried out, which has been developed within the German Collaborative Research Center Transregio 29 on IPS² Engineering. The case study simulates the lifecycle of a business-to-business PSS solution between two fictitious industrial companies (cf. Fig. 2). The PSS provider MicroS+ offers overall micro-milling solutions based on the machines themselves and related services. The Customer OMICHRON is a watch manufacturer and needs a micro-milling cell to produce high-quality wristwatch movement plates for the medium-priced segment.

Regarding the requirements of such a solution, the PSS provider MicroS+ proposes an availability-based offering, which requires a customer-provider relationship that relies on intense collaboration. Thus, the PSS provider is responsible both for the development and the delivery of the micro-milling process at the customer‟s site. This extension of the introduced lifecycle enables the PSS provider to control and improve the sustainability of the offered PSS continuously.

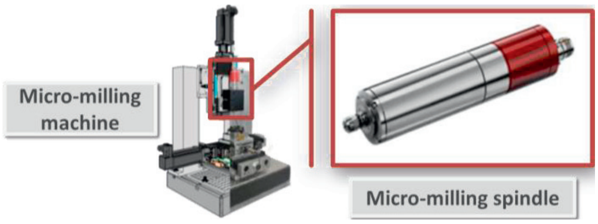

Fig. 2. The considered PSS module in the case study

For PSS-SAM application, the lifecycle of the representative micro-milling spindle as PSS module has been focused and divided into three main phases: the „planning & development", the „implementation", and the „operation" phases (cf. Fig. 3).

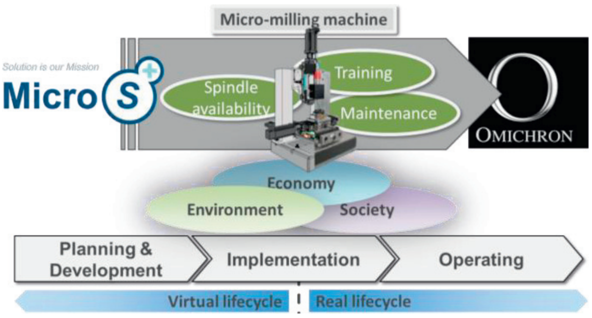

Fig. 3. PSS solution lifecycle and sustainability aspects.

The first phase is characterized by intellectual activities within PSS engineering. To meet the availability requirements, the planning and the development of product and service components are carried out in an integrated manner. Thus, the sustainability of PSS can, on the one hand, be enhanced through efficient planning of service activities adapted to the micro-milling cell. On the other hand, this can be achieved by allowing the reuse of used micro-milling spindles originating from other PSS. Furthermore, PSS requires enhanced competency of the involved personnel that supports the creation of new job opportunities.

In the implementation phase, the physical components of the PSS module are manufactured, transported, assembled, and the PSS is set up in the customer‟s production chain. At the same time, service execution capabilities (including the service partners) are planned and service personnel is trained.

In the operating phase, the provider runs the PSS and induces any expected and unexpected services to ensure the required availability. Thus, he accesses all operating data that include sustainability parameters such as energy consumption. Hence he can permanently control and improve the sustainability impact of the PSS.

3.2. *'Collection of PSS LIs' stage*

The PSS-SAM framework considers all sustainability dimensions (economic, ecological, and social). A Key Sustainability Indicator (KSI) has been then defined to assess the performance of a PSS solution in each of the above dimensions. To enable an integrated assessment, it is however necessary to consider PSS-specific performance as well.

Each of the four types of performance mentioned above depend, in turn, on single, selected LIs. Some LIs can be considered for different KSIs e.g. energy consumption for either economic or environmental performance. Economic LIs can e.g. be used to assess environmental and social costs, and enable their controlling. The allocation of LIs does not influence the final result as long as they are considered only once. Therefore, these indicators serve as a tool and constitute important input for the lifecycle-based assessment of PSS product performance in economic, environmental, and social matters [3]. Today, however, there are a number of difficulties or social concerns due to undefined social indicators (cf. chapter 1) [9]. Table 1 below outlines the hierarchical relationship between overall indicators, KSIs, and LIs [1].

Table 1. Relationship between overall indicators, KSIs, and LIs.

Overall indicators	KSIs	Examples of single LIs
Overall sustainability performance Overall data quality	PSS Economic performance: This indicator helps to control the economic aspects cumulated throughout the entire lifecycle of a PSS product.	Added value, gross profit, sales growth, return on sales, return on equity, the cost of PSS development, the cost of service processes, as well as the costs of infrastructure and spare parts.
	PSS Environmental performance: This indicator describes the fulfillment of ecological criteria of PSS products throughout the entire lifecycle.	Demand of energy, water, materials, and the extent of emissions, as well as the percentage of recycled materials.
	PSS Social performance: This indicator describes the fulfillment of social aspects of a PSS product throughout the entire lifecycle.	Number of training activities, degree of satisfaction of employees, customers, suppliers; health and safety prevention, the percentage of accidents, as well as job creation.
	PSS-specific performance: This indicator provides an assessment of PSS-specific values.	Order cycle time, reuse of goods, number of new customers.

Prior to selecting any environmental, economic, or social LIs, companies need to develop clear business strategies and set target definitions upon which an individual process of KSI definition must be established. Hence, definitions provided in this framework are general and must be adjusted to each case.

Due to the complex lifecycle of PSS products, indicators must meet several criteria, and they must be adapted to the developed framework. To implement indicators in corporate environments, they must thus show specific characteristics. An important criterion is that they must be simple and clear, i.e. they should be determinable with little time and effort. They must be easy to understand even for experts and no-experts alike. Another important aspect is that indicators require data that is difficult to obtain. Hence, data acquisition must be feasible and simple. To support the assessment process, indicators must be trusted and useful, and rules must be established to produce consistent results. Indicators must also be reusable in further assessments. Finally, they must be secure; information must be treated strictly confidentially and properly secured [16, 17].

In order to illustrate LIs calculation, the below paragraphs outline how some LIs of the case study presented in this paper have been calculated:

Single indicator 'Reuse of goods': As mentioned above, the value of offering a PSS solution is closely related to the performance and real utilization. To reduce the environmental impact and to increase economic efficiency, some items that have already been used but still meet the customer‟s requirements can be reused. This indicator specifies the amount of items deployed in a PSS that have been reused for the PSS solution.

Single Indicator 'Energy consumption': To calculate the energy consumption of PSS in the operating phase (product use, service delivery), different factors must be considered. Apart from the energy consumption of goods, the energy consumption in service delivery ($Q_{service}$) must be taken into account as well (e.g. tools used: $Q_{tools,}$ etc.). The total energy consumption can be calculated as follows:

$$\sum Q_{electricity}\,[\text{kWh}] = Q_{machine} + Q_{workplace} + Q_{service} \qquad (1)$$

The energy consumption of goods (e.g. machine, plant) can easily be measured by sensors. The energy consumption of tools that are used for service delivery can be calculated based on the power output (Ltools) and power efficiency (LNtools) of these tools:

$$Q_{tools}\,[\text{kWh}] = L_{tools} \cdot LN_{tools} \cdot T_{usage-time} \qquad (2)$$

The Calculation of $Q_{service}$ depends on the amount of service delivery and energy consumption of each delivery. Energy consumption ($Q_{workplace}$) of the surrounding area depends on the size of the site as well as the electric lighting and air conditioning facilities. The energy consumption of the electric lighting depends on the holding time and the required intensity of illumination. The intensity of illumination represents the incident light on a surface and is measured in lux. It can affect fatigue, performance, and accident rates of employees. For the workplace, an illumination of 1500 lux has been selected. If fluorescent lamps are used, an installed power of 0,03 kW per square meter workspace is scored. With regard to air conditioning, a power of 0,06 kW per square meter has been estimated as the requirement.

$$\sum Q_{workplace}\,[\text{kWh}] = Q_{light} + Q_{air\_condition} \qquad (3)$$

$$Q_{light}\,[\text{kWh}] = L_{lamps} \cdot T_{usage-time} \qquad (4)$$

$$Q_{air\_condition}[\text{kWh}] = L_{air\_condition} \cdot T_{usage-time} \qquad (5)$$

Single Indicator 'CO_2 emissions': A major cause for the emergence of CO_2 emissions is the use of fossil fuels for energy production. In the operating phase, energy is consumed by product use and service delivery (e.g. workers, tools). PSS usually consume and/or produce energy in the form of electric energy, thermal energy, cooling energy, and chemical energy. Considering service delivery, the energy needed for transportation must also be taken into account (i.e. usually chemical energy in fuel form).

$$CE_{total}\,[\text{kg}] = \sum CE_{electricity} + \sum CE_{TC} + \sum CE_{fuel} \qquad (6)$$

- CE = CO_2 emissions
- TC = thermal and cooling energy

As thermal and cooling energy can be neglected in the case study in hand, CE is calculated as follows:

$$CE_{total}\,[\text{kg}] = \sum Q_{electricity} \cdot E_{electricity} + \sum Q_{fuel} \cdot E_{fuel} \qquad (7)$$

- E = emission factor ($E_{electricity}$ = 0,616 [kg/kWh]; E_{fuel} = 2,854 [kg/l])

Single Indicator 'Job creation': This indicator assesses the impact of PSS use on the creation of new jobs. The use of PSS usually requires qualified workers. Therefore, PSS providers often hire workers, train them, and provide them to the customer. As a result of this, additional jobs are created by implementing a PSS solution. For the calculation of the single indicator „Job creation‟, the working hours of total PSS-related additional jobs are used as a unit.

Single indicator 'Employee satisfaction': There are many ways to define the indicator „employee satisfaction‟ depending on the company‟s goals. In this case study, „employee satisfaction‟ has been calculated based on survey results that consider the following aspects: safety climate, work days missing, salary of full time employees, employee suggestions implemented, and satisfied employee ratio.

3.3. 'Assessment of KSIs' stage

The PSS-SAM framework proposes to summarize KSIs assessment results in phase-specific reports. Figures 4, 5, and 6 show a tabular summary of the case study results. As shown in these Figures, in some cases some LSIs are not suitable for every PSS lifecycle phase. The selection of LSIs then depends on which PSS lifecycle phase is assessed. Furthermore, the choice of LSIs also depends on company-specific assessment goals, which are based on company requirements. The PSS-SAM framework proposes a list of possible LIs. This list is based in part on indicators defined by VDI guideline 4070 [8].

PSS planning and development phase:

		Selected Lifecycle Indicators (LIs)	Value	Data quality	Individual rating* (0-5)	Partial average
KSIs	PSS-specific performance	Reuse of parts	10%	1	4	3,5
		Availability	500 h	1	3	
	Economic performance	Development costs	80%	2	5	5
	Environmental performance	Energy consumption	200 kWh prim. energy	1	3	2,5
		CO2 emissions	123 kg CO2-eq.	1	2	
	Social performance	Employee satisfaction	4	3	3	3
		Job opportunities	1000 h	3	3	

Fig. 4. Assessment calculations for PSS lifecycle phase „planning and development".

PSS implementation phase:

		Selected Lifecycle Indicators (LIs)	Value	Data quality	Individual rating* (0-5)	Partial average
KSIs	PSS-specific performance	Service execution	30%	3	4	3
		Equipment setup	350 h	1	2	
	Economic performance	Implemen-tation costs	5%	2	3	3
	Environmental performance	Energy consumption	1370 kWh prim. energy	1	4	4,5
		CO2 emissions	1015 kg CO2-eq.	1	5	
	Social performance	Employee satisfaction	2	3	3	3,5
		Training of personal	50 h	1	4	

Fig. 5. Assessment calculations for PSS lifecycle phase „implementation".

PSS operating phase:

		Selected Lifecycle Indicators (LIs)	Value	Data quality	Individual rating* (0-5)	Partial average
KSIs	PSS-specific performance	Order cycle time	10%	1	3	3,5
		Availability	95%	2	4	
	Economic performance	Operating costs	15%	2	4	4
	Environmental performance	Energy consumption	3365 kWh prim. energy	1	2	2,5
		CO2 emissions	2416 kg CO2-eq.	1	3	
	Social performance	Employee satisfaction	3,2	3	3	3,5
		Service creation	430h	3	4	

Fig. 6. Assessment calculations for PSS lifecycle phase „operating".

The range for KSI performance goes from 1 (very low performance) to 5 (maximal performance).

„Data quality" of a KSI corresponds to the mean value of coefficients attributed to data used to calculate the respective LIs. The PSS-SAM framework suggests to apply the following classification of data on three levels [2]:

Coefficient 1 for high-quality data: Data from direct measurements and/or internal, reliable sources (e.g. ERP Systems) and specific to the analyzed process.

Coefficient 2 for medium-quality data: Data from external sources, which are specific to the analyzed process, e.g. supplier databases.

Coefficient 3 for low-quality data: Data from open source databases and/or not specific to the analyzed process.

3.4. 'Assessment of overall PSS sustainability performance' stage

The goal of this stage of the framework is to assess the „overall sustainability performance" and „overall data quality" of PSS solutions. The „overall sustainability performance" defines the sustainability degree of a PSS solution. It is based on the KSIs previously calculated for the different PSS lifecycle phases. As for the partial averages of KSIs, the range for „overall PSS sustainability performance" goes from 1 (very low performance) to 5 (maximal performance).

„Overall data quality" is a comprehensive indicator. It defines assessment reliability. The mean value of KSI „data quality" defines the degree of „overall data quality".

Figure 7 summarizes the calculation of the above overall indicators for the case study of this paper:

Entire PSS lifecycle

PSS lifecycle phase:		Planning & Development		Implementa-tion		Operating			
		Partial average	Partial data quality	Partial average	Partial data quality	Partial average	Partial data quality	Mean partial averages	Average partial of data quality
KSIs	PSS-specific performance	3,5	1	3	2	3,5	1,5	3,3	1,5
	Economic performance	5	2	3	2	4	2	4	2
	Environmental performance	2,5	1	4,5	1	2,5	1	3,2	1
	Social performance	3	3	3,5	2	3,5	3	3,3	2,7
Overall PSS sustainability performance								3,5	
Overall data quality degree									1,8

Fig. 7. Assessment calculations for the entire PSS lifecycle phase.

3.5. 'Controlling of PSS sustainability performance' stage

In this stage, the sustainability performance evaluated in the different phases is controlled on the basis of intervention limits defined by the company. The results show that the environmental performance that has been evaluated in the operating phase (cf. Fig. 6) exceeds the specific limit of 3200kWh defined by the company. As a result, overall PSS environmental performance has also surpassed the limit defined at 4900kWh. The reports of the development, implementation (cf. Fig. 5), and operating phase (cf. Fig. 6) demonstrate that performance must be increased in the operating phase of the PSS to achieve the environmental performance for the entire PSS. Therefore, in the next stage of the PSS-SAM, „stakeholder measures" must be run to develop a PSS solution that lies within the intervention limits defined by the company.

3.6. Stage 'stakeholders measures'

Regarding measure definition, the improved framework suggests to search critical points and define measures in PSS-relevant domains throughout its entire lifecycle. Furthermore, the framework invites stakeholders to determine whether a measure is to be implemented on the short, medium or long term. The below sections outline some examples of measures defined for the case study of this paper in different domains:

Changes to customers' ongoing operations: For the case study of this paper, energy consumption in the operating phase (cf. Figure 6) needs to be reduced to meet sustainability goals. Customer and PSS supplier need to find solutions to improve the customer"s ongoing operations. This may require changes to the PSS modules. A possible solution in this case is the reduction of energy in the milling process. This requires an analysis of the current milling process, e.g. to ensure that the electrical characteristic data of the milling spindle applies to the processed component. In addition, extreme standby time can increase energy consumption.

Changes to customer and PSS supplier organizational models: The customer of this case study is invited to integrate a sustainable management system into his quality management system, as defined by VDI guideline 4070 [8].

Since participation of PSS providers in customers" ongoing operations is a main characteristic of business to business PSS solutions, the PSS supplier may be invited to adapt his sustainable management respectively quality management systems as well.

4. Conclusion and outlook

The results of the case study presented in this paper have confirmed the usability of the improved PSS-SAM framework to assess the sustainability of multi-module PSS solutions. The framework can be implemented for PSS solutions with one or more modules and in different lifecycle stages.

Future work will cover the development of an assistant system that supports the PSS-SAM framework. The idea is to integrate this IT solution into CAD or PLM software. Furthermore, the framework will be improved to include solutions for compliance checking of PSS solutions against regulatory constraints such as laws, norms, labels, etc. The assistant system and improved framework will be validated in further use cases.

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